CLAIMS

1. A method for operating a preferably directly injecting internal combustion engine, in particular a diesel engine, which is operated in a first operating region associated with low to medium partial loads in such a way that combustion of the fuel occurs at a local temperature below the temperature of NO_x formation and with a local air ratio above the ratio at which particulates are formed, and in which fuel injection is initiated at a crank angle between 50° to 5° before top dead center of the compression phase and exhaust gas is recirculated at an exhaust gas recirculation rate of 50% to 70%, and where in a second operating region corresponding to medium partial loads, fuel injection is started in a range from about 2° crank angle before top dead center to about 20° crank angle after top dead center, and preferably in a range of about 2° crank angle before top dead center to about 10° crank angle after top dead center.

2. Method for operating a preferably directly injecting internal combustion engine, in particular a diesel engine, including the following steps:

   - operating the internal combustion engine in a first operating region corresponding to low partial loads, with essentially homogeneous mixture combustion and late fuel injection, the latter starting in a range of about 50° to 5° crank angle before top dead center of the compression phase;

   - operating the internal combustion engine in a second operating region corresponding to medium partial loads, with low-temperature mixture combustion and even later

injection than in the first operating region, said fuel injection starting in a range of about 2° crank angle before top dead center to about 20° crank angle after top dead center of the compression phase;

- with fuel being injected into the combustion chamber in the first operating region via first injection orifices and in the second operating region at least via second injection orifices of an injection valve preferably configured as a double needle nozzle.

3. Method for operating a preferably directly injecting diesel internal combustion engine with at least one piston reciprocating in a cylinder, where the internal combustion engine is operated in such a way that fuel combustion essentially occurs at a local temperature below the temperature threshold of NO_x formation and with a local air ratio above the limit of particulate formation, fuel injection starting in a range of 2° crank angle before top dead center to about 10° crank angle after top dead center of the compression phase and exhaust gas being recirculated at a rate of 20% to 40%, and where a piston with at least one squish surface and a toroidal piston recess and a constriction in the transition area between squish surface and piston recess is provided, and where on the upward stroke of the piston a squish flow directed from the outside into the piston recess is created and a turbulent base flow is initiated in the piston recess, and where the fuel is at least for the greater part injected into the toroidal piston recess and transported along the side wall of the piston recess and/or along the piston bottom, evaporating at least partially along the way.

4. Method for operating a preferably directly injecting diesel internal combustion engine with at least one piston reciprocating in a cylinder, where the internal combustion engine is operated in such a way that fuel combustion essentially occurs at a local temperature below the temperature threshold of NO_x formation and with a local air ratio above the limit of particulate formation, fuel injection starting in a range of 50° to 5° crank angle before top dead center of the compression phase and exhaust gas being recirculated at a rate of 50% to 70%, and where a piston with at least one squish surface and a toroidal piston recess and a constriction in the transition area between squish surface and piston recess is provided, and where on the upward stroke of the piston a squish flow directed from the outside into the piston recess is created, and where the fuel is at least for the greater part injected into the toroidal piston recess and transported by the squish flow along the side wall of the piston recess and/or along the piston bottom, evaporating at least partially along the way.

5. Method, in particular according to any of claims 1 to 4, **characterized in that** in the first operating region fuel is injected at a lower flow rate than in the second operating region.

6. Method, in particular according to any of claims 1 to 5, **characterized in that** in the first and second operating region fuel is injected in the shape of fuel jets forming a conical surface, the apex angle of the cone in the first operating region differing from that in the second operating region, preferably by being smaller in the former.

7. Method, in particular according to any of claims 1 to 6, **characterized in that** in the second operating region exhaust gas is recirculated with an exhaust gas recirculation rate of 20% to 40%.

8. Method, in particular according to any of claims 1 to 7, **characterized in that** fuel injection in the second operating region uses an injection pressure of at least 1,000 bar.

9. Method, in particular according to any of claims 1 to 8, **characterized in that** fuel injection in the first operating region uses an injection pressure between 400 to 1,000 bar.

10. Method, in particular according to any of claims 1 to 9, **characterized in that** in the first operating region the main part of combustion lies in the range of –10° to 10° crank angle after top dead center.

11. Method, in particular according to any of claims 1 to 10, **characterized in that** in a third operating region corresponding to high partial load or full load, the beginning of the main part of fuel injection takes place in a range from -10° to 10° crank angle after top dead center.

12. Method, in particular according to any of claims 1 to 11, **characterized in that** in the third operating region multiple injection is used.

13. Method, in particular according to any of claims 1 to 12, **characterized in that** in the third operating region the exhaust gas recirculation rate is 30% at most, and preferably 10% to 20%.

14. Method, in particular according to any of claims 1 to 13, **characterized in that** in the third operating region fuel is injected through the first and/or second injection orifices.

15. Method, in particular according to any of claims 1 to 14, **characterized in that** the overall air ratio lies between 1.0 and 2.0.

16. Method, in particular according to any of claims 1 to 15, **characterized in that** exhaust gas recirculation is performed externally and/or internally.

17. Method, in particular according to any of claims 1 to 16, **characterized in that** the swirl value is varied in at least one, and preferably in all, operating region(s) depending on load and engine speed.

18. Method, in particular according to any of claims 1 to 17, **characterized in that** the effective compression ratio is varied by shifting the closing time of at least one intake valve.

19. Method, in particular according to any of claims 16 to 18, **characterized in that** preferably at least in the first and/or third operating region internal exhaust gas recirculation is performed by opening the intake valve during the exhaust phase and/or opening the exhaust valve during the intake phase.

20. Method, in particular according to any of claims 1 to 19, **characterized in that** changeover from the first to the second operating region, respectively from the second to the first operating region, is initiated by reducing,

respectively increasing, the exhaust gas recirculation rate.

21. Method, in particular according to any of claims 1 to 20, **characterized in that** changeover from the first to the second operating region or vice versa is initiated by reducing the internal or external exhaust gas recirculation rate and by retarding the beginning of injection, respectively by increasing the exhaust gas recirculation rate and advancing the beginning of injection.

22. Method, in particular according to any of claims 1 to 21, **characterized in that** the decrease of the required exhaust gas recirculation rate on changing from the first to the second operational region is achieved by shifting the opening and/or closing time of the intake valve towards late.

23. Method, in particular according to any of claims 1 to 22, **characterized in that** the effective mean pressure in the first operating region is between 0 to 6 bar, and preferably between 0 to 5.5 bar.

24. Method, in particular according to any of claims 1 to 23, **characterized in that** the effective mean pressure in the second operating region is between 3.5 to 8 bar, and preferably between 4 to 7 bar.

25. Method, in particular according to any of claims 1 to 24, **characterized in that** the effective mean pressure in the third operating region is at least 5.5 bar, and preferably at least 6 bar.

26. Method, in particular according to any of claims 1 to 25, **characterized in that** in at least one operating region an intake flow with a swirl amounting to a swirl value ≥1 is generated in the cylinder, and that the fuel is transported by the squish flow along the side wall of the piston recess towards the piston bottom, evaporating at least partly along the way, and along the piston bottom to the center of the piston recess.

27. Method, in particular according to any of claims 1 to 26, **characterized in that** in at least one operating region a swirl-free intake flow, with a swirl value <1, is generated in the cylinder, and that the fuel is transported by the squish flow from the center of the piston recess along the piston bottom to the side wall of the piston recess and onwards to the constriction of the piston recess, evaporating at least partly along the way.

28. Method, in particular according to any of claims 1 to 27, **characterized in that** in at least one operating region a swirl-free intake flow, with a swirl value <1, is generated in the cylinder and that the fuel is transported by the turbulent base flow from the center of the piston recess along the piston bottom to the side wall of the piston recess and onwards to the constriction of the piston recess, evaporating at least partly along the way.

29. Method, in particular according to any of claims 1 to 28, **characterized in that** fuel is injected in the direction of the constriction of the piston recess, the intersection point of the jet axis of at least one injection jet at the start of injection lying for a great part of the fuel volume in an area between the side wall of the piston recess and the squish surface, which area comprises an

overhanging area of the side wall, the constriction and an inflow area between squish surface and constriction.

30. Method, in particular according to claim 29, **characterized in that** at low loads the intersection point is located in the overhanging wall area within the piston recess.

31. Method, in particular according to any of claims 29 to 30, **characterized in that** the intersection point is shifted in the direction of the constriction as the load increases.

32. Method, in particular according to any of claims 1 to 31, **characterized in that** the beginning of injection is advanced as the load increases from a range of 5° to 15° crank angle before top dead center, corresponding to a region of low partial load, to approximately 50° crank angle before top dead center.

33. Method, in particular according to any of claims 1 to 32, **characterized in that** fuel injection is performed at an injection pressure of 500 to 2,500 bar.

34. Method, in particular according to any of claims 1 to 33, **characterized in that** the main part of combustion is located in a crank angle range of 10° before top dead center and 10° after top dead center.

35. Method, in particular according to any of claims 1 to 34, **characterized in that** the overall air ratio is set between 1.0 and 2.0.

36. Method, in particular according to any of claims 1 to 35, **characterized in that** the internal combustion engine is

operated in at least one operating region with pulsed supercharging.

37. Method, in particular according to any of claims 1 to 36, **characterized in that** the closing time of at least one intake valve of at least one cylinder in at least one operating region is shifted towards early or late.

38. Method, in particular according to any of claims 1 to 37, **characterized in that** a maximum permitted injection volume is computed from a minimum permitted air/fuel ratio and an actually measured fresh-air mass or an actual air/fuel ratio.

39. Method, in particular according to any of claims 1 to 38, **characterized in that** at least one actual value of a combustion parameter required for controlling combustion is computed as a weighted mean of the values in preceding individual cycles.

40. Method, in particular according to any of claims 1 to 39, **characterized in that** at least one control parameter of a combustion controller is adapted as a function of the desired target value.

41. Method, in particular according to any of claims 1 to 40, **characterized in that** during at least one deceleration phase of the internal combustion engine the intake flow is at least throttled, and preferably cut off, and that preferably unthrottled exhaust gas recirculation is carried out.

42. Internal combustion engine, particularly a diesel internal combustion engine with direct injection, in particular for

implementation of the method according to any of claims 1 to 41, with a fuel injection system and an exhaust gas recirculation system, wherein the beginning of fuel injection may be varied in at least one operating region between 50° before top dead center and 20° after top dead center, and preferably up to 50° after top dead center, and wherein the exhaust gas recirculation rate may be varied between 0 and 70%.

43. Internal combustion engine, in particular for implementation of the method according to any of claims 1 to 41, with an injection valve for direct fuel injection into the combustion chamber, which injection valve is designed as a double needle nozzle having first and second injection orifices, said first and second injection orifices being controlled separately.

44. Internal combustion engine, especially a diesel internal combustion engine with direct injection, in particular for implementation of the method according to any of claims 1 to 41, in which the beginning of fuel injection can be set in a range of 50° to 5° crank angle before top dead center of the compression phase, and which has an exhaust gas recirculation system with exhaust gas recirculation rates between 50% to 70%, and which is provided with at least one piston reciprocating in a cylinder, said piston having on its top face at least one squish surface and a toroidal piston recess with a constriction, side walls and bottom with essentially concave curvature and an overhanging wall area between side wall and constriction, wherein at least one jet axis of a fuel injection jet of the injection device for the greater part of the injected volume is directed at the beginning of injection towards an area between the side wall and the squish surface, which area

comprises the overhanging wall area, the constriction and an inflow area between squish surface and constriction.

45. Internal combustion engine, especially a diesel internal combustion engine with direct injection, in particular for implementation of the method according to any of claims 1 to 41, in which the start of fuel injection can be set in a range of 2° crank angle before top dead center and 10° crank angle after top dead center of the compression phase, and which has an exhaust gas recirculation system with exhaust gas recirculation rates between 20% to 40%, and which is provided with at least one piston reciprocating in a cylinder, with the piston having on its top face at least one squish surface and a toroidal piston recess, the recess having a constriction, side walls and bottom with essentially concave curvature and an overhanging wall area between side wall and constriction, and where at least one jet axis of a fuel injection jet of the injection device for the greater part of the injected volume is directed at the start of injection towards an area between the side wall and the squish surface, which area comprises the overhanging wall area, the constriction and an inflow area between squish surface and constriction.

46. Internal combustion engine, in particular according to any of claims 42 to 45, **characterized in that** fuel injection pressure can be varied between at least a first and a second pressure level, the first pressure level preferably covering a range of up to 1,000 bar and the second pressure level covering a range of at least 1,000 bar.

47. Internal combustion engine, in particular acccording to any of claims 42 to 46, **characterized in that** a device for varying the swirl level is provided.

48. Internal combustion engine, in particular according to any of claims 42 to 47, **characterized in that** a device for varying the opening and/or closing time of the at least one intake valve is provided.

49. Internal combustion engine, in particular according to any of claims 42 to 48, **characterized in that** the timing of the intake valve and/or the exhaust valve can be shifted by means of a phase shifting device.

50. Internal combustion engine, in particular according to any of claims 42 to 49, **characterized in that** at least one intake valve can be activated during the exhaust phase.

51. Internal combustion engine, in particular according to any of claims 42 to 50, **characterized in that** at least one exhaust valve can be activated during the intake phase.

52. Internal combustion engine, in particular according to any of claims 42 to 51, **characterized in that** the first injection orifices have a smaller total flow cross-section than the second injection orifices.

53. Internal combustion engine, in particular according to any of claims 42 to 52, **characterized in that** the axes of the first injection orifices are aligned along a first conical surface and the axes of the second injection orifices are aligned along a second conical surface, the apex angle of the first conical surface being smaller than the apex angle of the second conical surface.

54. Internal combustion engine, in particular according to any of claims 42 to 53, **characterized in that** the first and

second nozzle needle are coaxial, the first nozzle needle preferably being guided in the second nozzle needle, which is configured as a hollow needle.

55. Internal combustion engine, in particular according to any of claims 42 to 54, **characterized in that** the first and the second nozzle needle are placed in parallel side by side in a nozzle holder.

56. Internal combustion engine, in particular according to any of claims 42 to 55, **characterized in that** the internal combustion engine can be operated in at least one operating region with pulsed supercharging.

57. Internal combustion engine, in particular according to any of claims 42 to 56, **characterized in that** in at least one intake pipe a quick-acting pulse switching element is provided, said pulse switching element preferably having switching times - from a first extreme position to a second extreme position and back to the first one - of 10 ms at most, and more preferably at most 8 ms.

58. Internal combustion engine according to claim 57, **characterized in that** the pulse switching element is configured as a flap.

59. Internal combustion engine according to claim 57, **characterized in that** the pulse switching element is configured as a slide valve, preferably a rotary slide valve.

60. Internal combustion engine according to any of claims 42 to 59, **characterized in that** the closing time of the intake

valve can be shifted towards late in at least one operational region.

61. Internal combustion engine, in particular according to any of claims 42 to 60, **characterized in that** the intersection point of the at least one jet axis of the fuel jet can be varied at the beginning of injection at least between the overhanging wall area and the constriction.

62. Internal combustion engine, in particular according to any of claims 42 to 61, **characterized in that** the piston recess is dimensioned such that the relation $0.5 < D_B/D < 0.7$ is valid for the ratio of maximum piston recess diameter to piston diameter.

63. Internal combustion engine, in particular according to any of claims 42 to 62, **characterized in that** the piston recess is dimensioned such that the relation $0.12 < H_B/D < 0.22$ is valid for the ratio of maximum piston recess depth to piston diameter.

64. Internal combustion engine, in particular according to any of claims 42 to 63, **characterized in that** the piston recess is dimensioned such that the relation $0.7 < D_T/D_B < 0.95$ is valid for the ratio of constriction diameter to maximum piston recess diameter.

65. Internal combustion engine, in particular according to any of claims 42 to 64, **characterized in that** the inflow area is configured as an annular depression between squish surface and constriction.

66. Internal combustion engine, in particular according to any of claims 42 to 65, **characterized in that** the depression has a plane bottom leading into the piston recess.

67. Internal combustion engine, in particular according to any of claims 42 to 66, **characterized in that** the depression has depth of between 5% to 15% of the maximum recess depth.

68. Internal combustion engine, in particular according to any of claims 42 to 67, **characterized in that** the depression has an at least partially cylindrical wall.

69. Internal combustion engine, in particular according to any of claims 42 to 68, **characterized in that** the diameter of the depression in the region of the wall is 10% to 20% greater than the diameter of the constriction.